Cold Survivable Distributed Motor Controller (CSDMC)

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Abstract — **This paper presents the results of NASA's COLDTECH development entitled "Cold Survivable Distributed Motor Controller (CSDMC)". This work addresses the need to lower the mass, power and volume of the motor control electronics and its associated cabling. Landed payload mass of ocean world missions typically requires a spacecraft launch mass of 7-10x the landed mass due to the required propellant to get the payload to the surface. Reduction of landed mass leads to cheaper, more frequent missions and/or increased science return.**

This work addresses this need by developing a distributed electronics architecture, which places control and power electronics near or at actuators and instruments. The outcome of this effort will result in a 10X reduction in harness mass, enabling a significant increase in science payload which then enables more capable sample acquisition, delivery and analysis systems on these missions.

Placing the control and power conversion electronics at or near the actuators or instruments is the cornerstone of our distributed architecture. To do this, we developed the technology necessary to distribute the electronics and place them on a shared interface and power bus. This enables a significant reduction in cable mass along with its associated complexity. This allows spacecraft designers to take advantage of volume at the extremities that would normally not be utilized.

In this paper we discuss the technologies and system design to achieve these goals in support of ocean world missions. These technologies include the development of our motor control modules, a point of load regulator and isolated converter modules along with the packaging technology necessary to allow our electronics to survive the extreme temperatures.

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1. INTRODUCTION

Conventional practice, as illustrated in figure 1, is to house actuator electronics in a protected, centralized, warm electronics box (WEB), requiring highly complex, point-to-point wiring to connect the drive and control electronics to the actuators and instruments, usually located at the system appendages. The complexity of actuators used in current mission architectures require 10 or more individual wires per actuator routed individually between the centralized controller and the actuator. The Mars Science Laboratory (MSL) cables were several meters long and accounted for over 50Kg of the rover mass. Furthermore, as illustrated in figures 2 and 3, these cables represented a significant complexity for the mission, they were a significant source of thermal heat loss within the rover, they increased Electromagnetic Interference (EMI), and they increased the stiffness in the robotic arm.

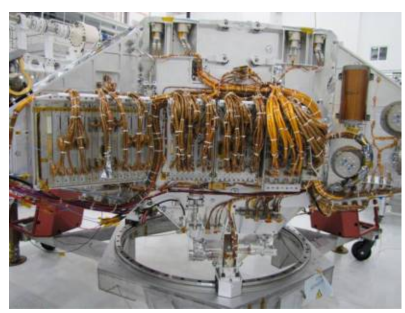


Figure 1: MSL Wiring Harness

Figure 2: Integration and Test

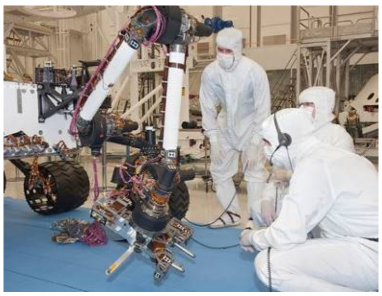


Figure 3: MSL's Robotic Arm

Illustration of cabling mass and complexity in current landed mission architectures across all subsystems and phases of development.

We solved this problem by utilizing a distributed motor control (DMC) technology that minimizes the dependency of the motor controller on the WEB, eliminate the point-to-point wiring, and reduce the wire count by two orders of magnitude with concomitant savings in mass, cost and complexity. Additional benefits include:

- minimization of thermal losses by minimizing cables leaving the warm compartment.
- greatly improved noise immunity, and reduced EMI which results in improved actuator control and repeatability.

Table 1 provides a comparison of historical actuator cable mass versus the proposed implementation. This study showed that actuator harness mass represents 25 - 33% of the total harness mass. Distributed motor control will reduce the actuator harness mass by 90% to 1.8Kg. [1,2]

Rover System	Pathfinder	MER	MSL
Total Wiring Mass	1.4 Kg	10.4 Kg	52.7 Kg
Actuator Wiring Mass	0.35 Kg	3.0 Kg	17.4 Kg

Table 1: Benefits of a Distributed Motor Control (DMC)

2. PROJECT GOAL

As compared to current architecture implementations, placing the control and power conversion electronics at or near the actuators/instruments is the key change that lies at the core of our distributed architecture. To make this change, we developed the technology necessary to distribute the electronics and place them on a shared interface and power bus. A comparison of a motor control architecture using current state of practice versus the proposed solution is shown in figure 4. Each actuator to controller wire shown in figure 4 represents 20 wires routed individually to each actuator, representing 0.8Kg of cable mass per motor. Figure 5 illustrates the reduction in cable mass and complexity when each motor has distributed control and power electronics and is connected to a shared power and control bus.

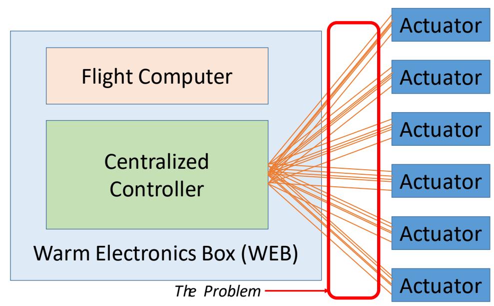


Figure 4: Current state a practice: Point to point wiring

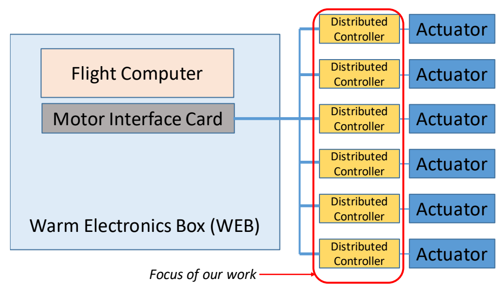


Figure 5: Distributed Motor Control Electronics

Illustration of the solution to the problem: Distributing the controller electronics out at the actuators, and connecting them through a common power and interface bus.

The goal of our effort is to decrease in the volume (10x), and mass (3x), of electronic assemblies through the use of advanced packaging technology. The energy required to keep the electronics warm is reduced by allowing the electronics to be stored at the ambient environment and heated prior to operation. As illustrated in Table 2 the power required for survival heating is eliminated because the CSDMC can be stored down to Europa ambient temperatures. [5]

Cold Survivable Distributed Motor Controller Goals	
Volume	< = 10cm x 10cm x 3cm
Mass	< 0.33Kg
Temp	Storage temp down to -180C

Table 2: Volume, Mass, and Thermal Goals

3. SYSTEM DESIGN

Figure 6 provides a more detailed view of the architecture with an expanded Cold Survivable Distributed Motor Controller (CSDMC). Our architecture optimally divides motor control between the warm box computer, which performs all mission dependent functions including control loop closure and associated algorithms, and the cold module which provides the motor and sensor interface, analog/digital conversion, and commutation. This architecture minimizes the number of components residing in the cold module, thus minimizing cold module mass, volume, cost and risk. The highlighted areas in Table 2 outline the work covered under our NASA COLDTECH funded activity. This work addressed the radiation and temperature survivability of existing electronics along with developing the remaining reduced Space, Weight and Power (SWaP) building blocks of the distributed power conversion system, i.e., point-of-load regulator and isolated converter.

This work built upon the NASA's Game Changing Ultra Low Temperature Electronics task. [3] Under this task we developed compact avionics technologies to address the Command & Data Handling (CDH), Power and Motor Control needs for mission concepts to ocean worlds. These potential missions include a potential Europa Lander. This funding is used to develop the development of motor driver and resolver modules. The remaining modules are funding through a Europa Lander focused technology effort.

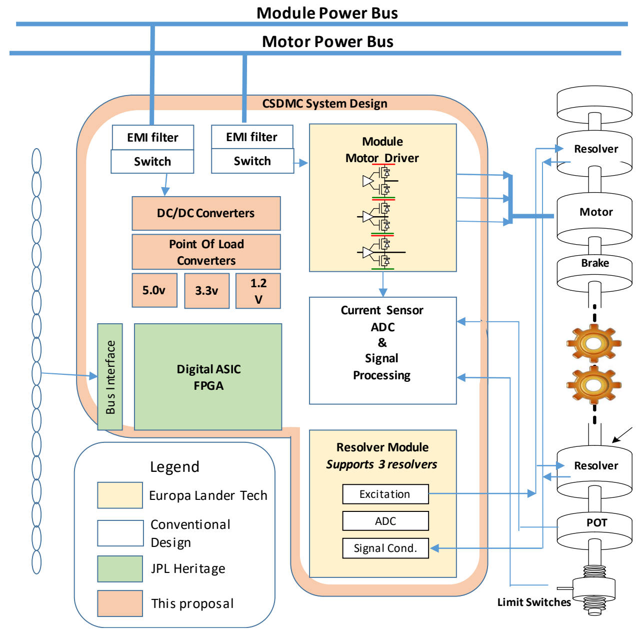


Figure 6: CSDMC System Block Diagram

Illustration of the components that build up our Cold Survivable Distributed Motor Controller (CSDMC) in its initial for motor control. Our technology will enable a 10X reduction in cable mass for motor control, remote control and state monitoring applications

The CSDMC is constructed of modules developed under NASA and JPL internal investment. As illustrated in Figure 8 the following modules were developed:

1. Motor Driver Module: This module implements a 3 phase h-bridge for driving the motors. This module is currently capable of drive 3A motors.

2. Resolver Module: This module is able to interface with three resolvers. These resolvers are used for motor commutation and output position sensing.

3. Current Sense Module: This module allows for the sampling of motor phase currents.

4. LVDS Module: This provides a standardized interface to the spacecraft flight computer. [4]

5. POL Module: This module implements point of load regulation. One module is needed for each of the three different voltages that are needed locally on the CSDMC.

6. Isolated Converter Module: This module provides for the DC to DC conversion needed to provide an isolated power system for the CSDMC.

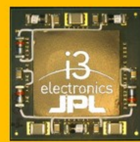
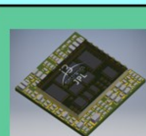
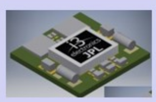
Technology	Picture
Motor Driver Module	
Resolver Module	
Low Voltage Differential Switching (LVDS) Module	
Current Sense Module	
Point of Load Regulator Module	
Isolated Converter Module	

Figure 8: CSDMC Advanced Packaged Modules

4. Motor Driver Module

The Motor Driver Module was the first module constructed under this effort. The module consists of the electronics necessary to drive a 3A brushless DC motor. This module consists of three MOSFET based half bridge drivers along with a radiation hardened MOSFET driver. The module consists of the MOSFET and driver die along with its associated discrete circuitry. The device was developed in partnership with i3 Technologies. JPL performed the electronic design and breadboard testing. i3 performed the detailed module design. Once constructed the modules were sent to JPL for testing.

The design done by i3 consisted of schematic entry, module layout, mechanical analysis, thermal analysis, and production setup. Figure 9 shows the completed module design along with a picture of module.

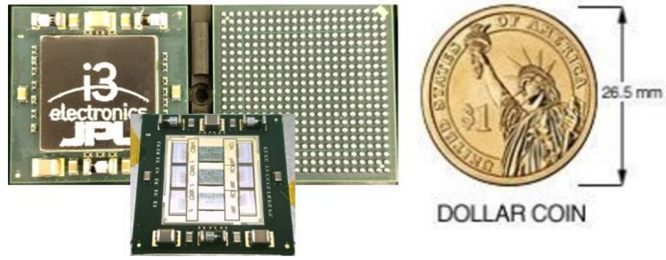


Figure 9: M1 Motor Driver Module.

5. Resolver Module

As illustrated in Figure 10, the Resolver Module was the second module constructed. The module consists of the electronics necessary to implement three resolver interfaces. Resolvers are used to measure position of our motors. A resolver interfaces is allocated for shaft position both before and after the gear box. As illustrated in Figure 11, this module consists of excitation circuitry, input filter circuitry and the Analog To Digital Conversion circuitry to present the information to a FPGA for angle tracking processing. The device was developed in partnership with i3 Technologies. JPL performed the electronic design and breadboard testing. i3 performed the detailed module design. Once constructed the modules were sent to JPL for testing.

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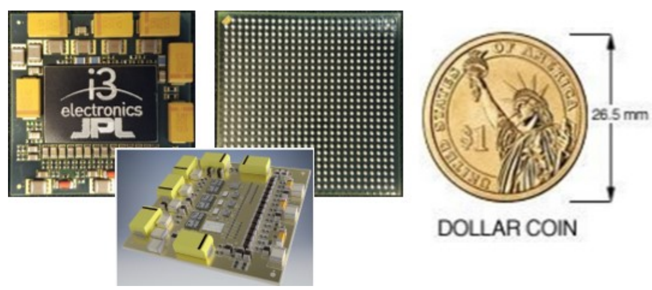

Figure 10: Resolver Module.

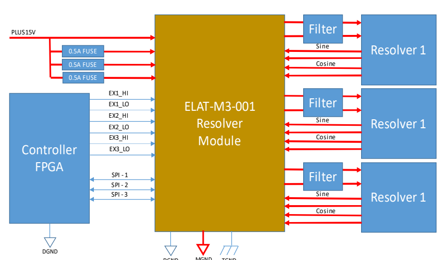

Figure 11: Resolver Module Block Diagram

6. CURRENT SENSE MODULE

Another module we are currently constructing is the Current Sense Module. This modules function is to digitize the motor phase currents along with collecting telemetry for the CSDMC. As illustrated in figure 12, the Current Sense Module contains two A/Ds and signal conditioning circuitry to handle the current monitoring and housekeeping needs of one motor channel. This is accomplished with two high side bi-direction current sensors for motor phase current and two low side current sensors for brake current and motor bridge or heater current.

This module is currently under construction at i3. We expect to receive this module in April 2018 and begin testing shortly thereafter.

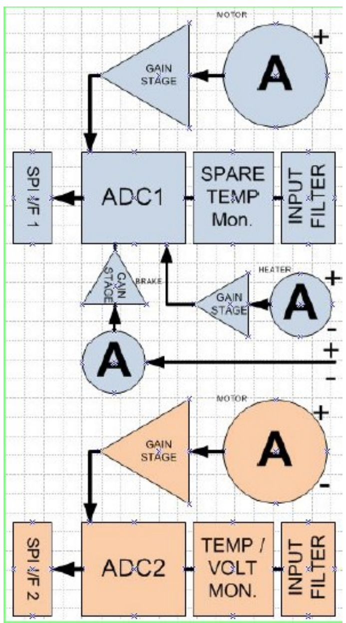

Figure 12: Current Sense Module Block Diagram.

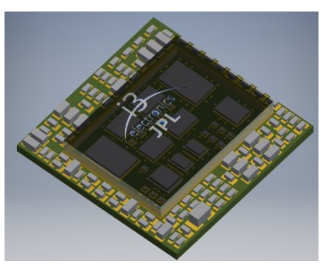

Figure 13: Current Sense Module.

7. POINT OF LOAD MODULE

As illustrated in figure 13, the Point of Load (POL) module together with an external inductor and capacitors tuned to its application implements a point of load regulator. This module provides 300K radiation tolerant, dual gallium nitride (GaN) technology solution for a non-isolated Buck Converter, optimized to meet specific circuit requirements needs for the Europa Lander motor controller. This 90% efficient non-hermetic BGA reduces power consumption compared a linear regulator, the current state of practice for local power conversion. The small size allows its use on every board allowing a board to have power delivered at higher voltages and lower currents. This eliminates mass of connectors for multiple power connections coming in from other boards.

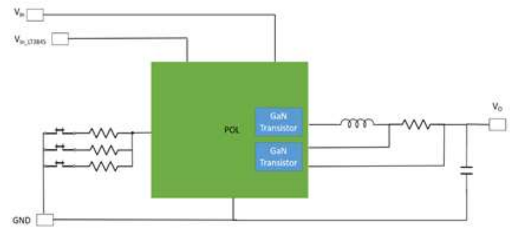

Figure 13: Point Of Load Module Block Diagram

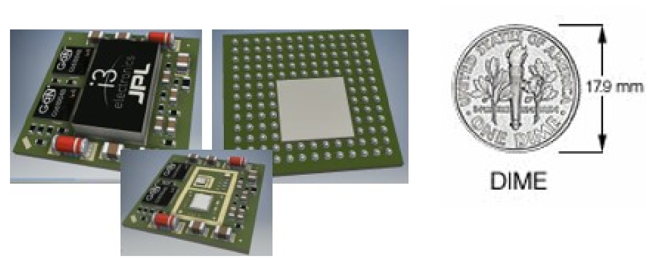

Figure 14: Point Of Load Module.

The features of this module are as follows:

- Input Voltage: 10.8V – 36V
- Output Voltage1: 1.231V – 36V
- Output Current up to 10A
- Efficiency > 90% (5V input, 3.3V)
- Buck Converter Topology
- Adjustable switching frequency (100kHz – 390kHz)
- Input voltage under voltage protection
- 300KRAD Tolerant
- 17.8 mm x 17.8 mm compact size
- Storage temperature as low as -180C
- Over current protection

i3 performed electrical, thermal and mechanical analysis. Electrical evaluated high current distribution, return paths, I*R loss, supply path and power dissipation. Thermal and mechanical analysis evaluated substrate design and process as it affects warpage during assembly and stress related to operational and non-operational environmental conditions, copper balance, tensile and flexural modulus, CTE, and junction temperatures. Analysis results shown below indicate no outstanding issues from temperature rise, substrate warpage due to assembly process or die stresses over temperature.

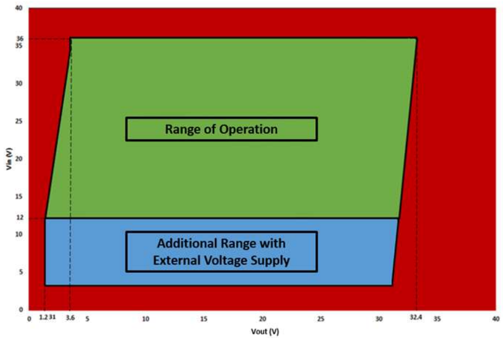

Figure 15: Voltage In vs Voltage Out – Range of use

The performance of this module was characterized across a wide range of input voltages and output voltages. The following figure shows the performance of the POL module when operating at a 3.3volt output.

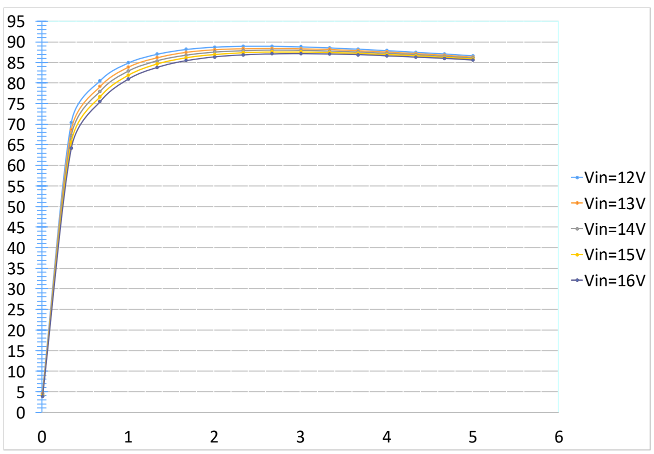

Figure 16: Efficiency of the POL Module

8. AS NEEDED RADIATION SHIELDING

One of the key challenges for Europa Orbiter and Lander is procuring parts that meet the 300K radiation requirements. The Voltage regulator selected for the dPOL had a rating performance of only 200K rads, requiring additional radiation shielding beyond what is provide by the landed systems. Figure 17 shows the 360 degree shielding approach for the POL module using three tantalum elements: the BGA s Shield, the Die Shield and Top Cover Shield, which seconds as a protective cover for the wirebonds during testing and handing. The analysis performed at JPL; refer to Figure 11b, which shows the total dosage performance with and without shielding. [5] Results show the three layer shielding design met the total dose radiation mission requirements.

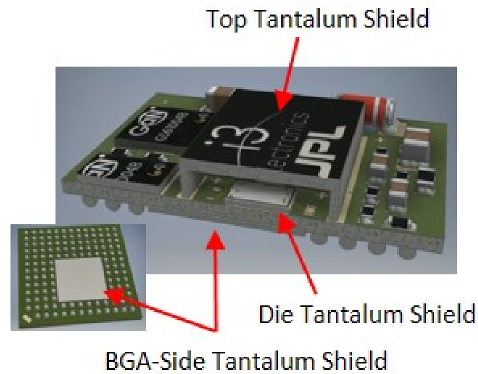

Figure 17. Radiation Shield for the POL

	TID (krad) on Si Die in Point of Load Module										
	Case 1: No Ta, Carved CoreEZ bottom				Case2: Al-filled CoreEZ bottom				Case3: 0.125mm Ta on Co		
	Proton	Photon	Electron	subtotal	Proton	Photon	Electron	subtotal	Proton	Photon	Elec
Lander	1.32E-01	1.98E+00	4.22E+01	4.43E+01	9.83E-02	1.77E+00	3.12E+01	3.31E+01	9.62E-02	1.80E+00	2
DOV	2.09E-02	3.80E-01	6.15E+00	6.55E+00	1.78E-02	1.85E+00	5.89E+00	7.76E+00	1.64E-02	3.50E-01	5

Figure 18: TID simulation results.

In order to prove that our POL module would survive the radiation environment we did Co60 testing of the module to supplement our analysis shown above. Co60 produces radiation that is unaffected by the shield or the electronic packaging. As mentioned above the shielding reduces the TID requirement down to 200Krad for the device. The intent was to show tolerance up to 200Krad.

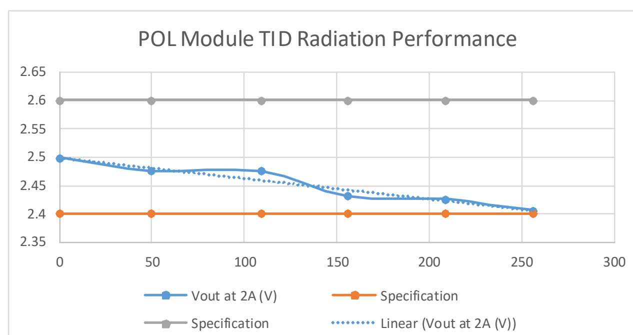

Figure 19: TID Test Results for POL Module.

The results shown above show the regulated output as a function of exposed dose. The module output drifts down until it is non-compliant with our requirements at 256 Krad. This testing shows our POL our shielding approach will allow this part to be used to 356Krad and beyond.

9. Miniaturized Packaging Design

The packaging for the CSDMC allows for a compact package size of 10cm x 10cm x 3cm. This compact size allows for the motor electronics to be packaged at the actuators. The electronics is small enough to fit with the structure of robotic arms or to be packaged along with the actuators. An illustration of our packaging approach is shown in figure 19 and 20.

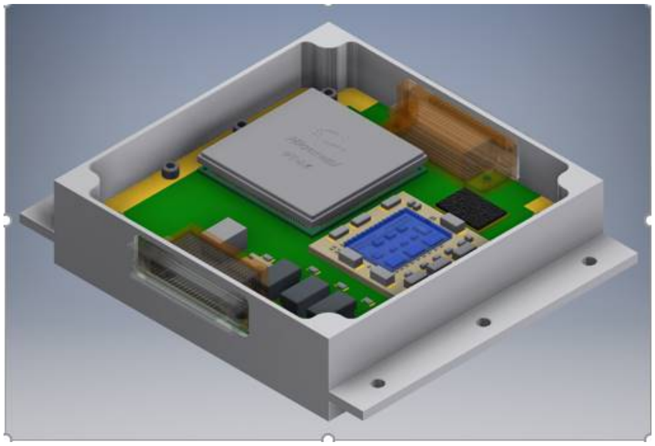

Figure 19 : Cold Survivable Distributed Motor Controller

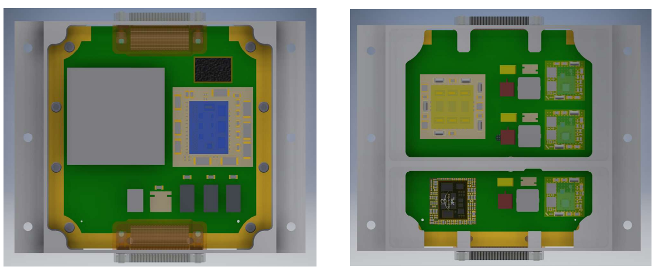

Figure 20: Cold Survivable Distributed Motor Controller

As illustrated above Miniaturized Motor Controller, the packaging for this motor control assembly is based upon a slice based architecture originally developed for JPL's X2000 program [2]. The entire package fits within a 10cm x 10cm x 3cm volume. Features of the CSDMC are as follows:

- Controls 1X - 3A Brushless DC Motor
- Constructed out of already developed modules
- Features
- 2 Resolver channels
- 1 Brake Driver per motor channel
- 1 Motor Driver
- Point of Load Regulation
- Supports resolver, hall sensor or encoder for commutation
- 28 Volt power bus
- On board commutation and control logic
- Compact 10cm x 10cm x 3cm design
- CMC Mass CBE = 0.3Kg; Vol CBE = 300cm3
- Survival temperature: -180C to +125C
- Operation temperature: -55C to +85C

10. Summary

Landed payload mass of ocean world missions typically requires a spacecraft launch mass of 7-10x the landed mass due to the required propellant to get the payload to the surface. We have developed technology to resduce this landed mass by enabling a distributed electronics architecture, which places control and power electronics near or at actuators and instruments. The outcome of this effort will result in a 10X reduction in harness mass, enabling a significant increase in science payload which then enables more capable sample acquisition, delivery and analysis systems on these missions.

We addressed by combining JPL s expertise in cold capable electronics, packaging and power conversion together with the state-of-the-art high density interconnect technology. This combination will result in a unique high density technology that extends the life of landed missions and also allows the missions to do more science through the mass and volume that is made available.

We have demonstrated the components necessary for the distributed architecture and a system design that integrates the required technologies to achieve landed mass reductions in support of ocean world missions.

11. Acknowledgement

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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12. References

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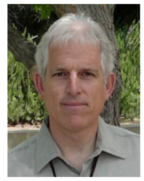
13. Biography

Gary Bolotin received a M.S. in Engineering from University of Illinois at Urban Champaign in 1985 and a B.S. in Engineering from Illinois Institute of Technology in 1984. He has been with JPL for more than 32 years. He is currently the lead of the Europa Lander Motor Controller. He has also managed engineering teams as both team leads and line manager at the section and group level.

Don Hunter has been with the Jet Propulsion Laboratory and a member of the Advanced Electronic Packaging Engineering section since 1993. Major contributions include; development of ruggedized 6U-VME fight system design for the Mars Pathfinder Mission, holds several Cal Tech and US Patents for work in advanced packaging systems architectures He holds a B.S. in mechanical engineering/Industrial Design from California State University Los Angeles and has been involved in the electro-mechanical packaging environment for over 28 years. He possesses experience ranging from commercial applications of deck top test equipment to military (DOD) cold temperature and high-G integrated packaging applications.



Doug Sheldon received a B.A. in Physics from the University of Colorado, M.S. in Physics from University of Oregon and D.M. in Management from Colorado Technical University. He has been with JPL since 2003. He currently manages the Assurance Technology Program Office for JPL

Chris Stell holds a Bachelor of Science in Engineering degree from California State University Northridge (May 1986). Is a Principal Engineer at the Jet Propulsion Laboratory and employed since 1992. He has over 30 years experience designing power electronics for space applications.

Malcolm Lias holds a B. S. in Electrical Engineering from Rochester Institute of Technology. He is currently developing Motor Control Card for Europa Lander at Jet Propulsion Laboratory (JPL). Testing and documenting the Distributed Motor Control Multi-Chip Module for use on the Europa Lander. Prior to joining JPL Malcom worked for Wordword Inc where he was responsible for design, product support, and testing of control electronics for missiles, smart bombs, and aircraft. Member of teams to promote corporate initiative.